Swarm Robots Using Lévy Flight in Targets Exploration -Computer Simulation for Performance of Lévy Flight with Constant and Updated Minimum Movement Time-

Yoshiaki Katada[1†]

[1]Department of Electrical and Electronic Engineering, Setsunan University, Osaka, Japan
(Tel: +81-72-839-9148; E-mail: katada @ ele.setsunan.ac.jp)

Abstract: This study tackles the task for swarm robotics where robots explore the environment to detect many targets. When a robot detects a target, the robot must be connected with a base station via intermediate relay robots for wireless communication. In our previous results, we confirmed that Lévy flight outperformed the usual random walk for exploration strategy in real robot experiments. This paper investigated the performance of Lévy flight varying minimum movement time in navigation through a series of computer simulations and proposed the update method of the minimum movement time. The results suggest that the search efficiency of Lévy flight has an optimal value for minimum movement time and the performance of Lévy flight with the update method fell between the best and worst performance with constant parameter setting for minimum movement time.

Keywords: Swarm Robotics, Lévy Flight, Navigation, Mobile Robots.

1. INTRODUCTION

Swarm Robotics (SR) [1] have attracted much research interest in recent years. Generally, the tasks in SR are difficult or inefficient for a single robot to cope with. Thus, you find overlap between SR and multi-robot systems. Şahin [2] enumerated several criteria[1] for distinguishing swarm robotics as follows:

- autonomy: Each robot should be physically embodied and situated.
- redundancy: Group sizes accepted as swarms is 10 to 20.
- scalability: SR system should be able to operate under a wide range of group sizes.
- simplicity: Each robot should employ cheap design, that is, the structure of a robot would be simple and also the cost of it would be cheap.
- homogeneity: SR system should be composed of homogeneous individuals. This enhances the above 2nd and 3rd criterion.

According to the last criterion, homogeneous controllers for individuals are desirable for SR systems. Additionally, this approach does not assume the existence of an explicit leader in swarm robots due to the above criteria. This results in that a collective behavior emerges from the local interactions among robots and between the robots and the environment. Therefore, it is required for SR systems that individuals in swarm show various behaviors through interactions although the individuals are homogeneous.

The typical control tasks in SR are navigation, aggregation, formation and transport requiring distributed collective strategies [1]. In this paper, we copes with a target detection problem, which is one of navigation problems. In this control task, several robots can communicate with each other via wireless communication networks (WCN) [3] due to the multi-hop transmission to achieve collective exploration. As soon as a robot detects a target, the information is sent from the robot to the base station via intermediate relay robots. Therefore, all robots should be "connected" to the base station via WCN.

Our research group investigated communication range and the number of robots required for a SR network to achieve connectivity based on percolation theory in computer simulation [4]. According to the results obtained in [4], we conducted a series of real experiments [5]. Also, we must consider the performance of exploration as well as connectivity of the SR network in a target detection problem. Therefore, we improve exploration strategies to enhance the performance.

In a target detection problem which we cope with, we assume that robots have no prior knowledge of the environment. In these scenarios, a random walk seems to be appropriate for exploration strategy. It has been reported in the literature [6, 7] that some species show a specific random walk, Lévy flight [8], when prey are sparsely and randomly distributed. This condition might correspond to a target detection problem. In our previous works[9], we conducted a series of real experiments on a target detection problem by swarm robotic network in order to investigate the effect of the step size of the random walk and the number of robots. We confirmed that Lévy flight outperformed the usual random walk for exploration strategy in real robot experiments. In computer simulation [10], we investigated which probability distribution for Lévy flight shows best performance in many target detection problem varying its parameters and confirmed that the probability distribution which adopted in [9] was best. For integrating Lévy flight to real robots, we must set some parameters with regard to the experience of the real experiments. Those parameters would affect the performance of Lévy flight as well as the probability

† Yoshiaki Katada is the presenter of this paper.
[1] Şahin [2] claimed that these criteria should be used as a measure of the degree of SR in a particular study.

distribution.

This paper investigated the performance of Lévy flight in targets detection problem varying one of the parameters described above, minimum movement time, and proposed the update method of it through a series of computer simulations. The paper is organized as follows. The next section explains Lévy flight. Sect. 3 shows the structure of the simulated mobile robots. Sect. 4 describes the controller of the robots and how to implement Lévy flight in the controller, respectively. Sect. 5 investigates the performance of Lévy flight with constant minimum movement time. Sect. 6 investigates the performance of Lévy flight with the update method of the minimum movement time. Conclusions are given in the last section.

2. LÉVY FLIGHT

A random walk with a constant step size is well known. On the other hand, Lévy flight is a random walk whose step size varies according to a Lévy probability distribution [8]. Lévy probability distribution for a step size, w, is formulated as follows:

$$L_{\alpha,\gamma}(w) = \frac{1}{\pi}\int_0^\infty e^{-\gamma q^\alpha}\cos(wq)dq, \quad \gamma > 0, \ w \in R \qquad (1)$$

where γ is the scaling factor and α ($0 < \alpha < 2$) is a parameter varying the shape of the probability distribution.

Lévy probability distribution for a step size can be approximated in the following [11]:

$$L(w) \propto w^{-\alpha} \qquad (2)$$

According to the recommendation in [9, 12], we define it as follows:

$$L(w) \equiv w^{-1.2} \qquad (3)$$

Fig. 1 shows Eq. (3) over the range $1 \leq w \leq 30$. In computer simulation on many target detection problem[10], we compared the performance of Eq. (3) with those of the other formulations of Lévy probability distribution and confirmed that Eq. (3) shows the best performance in the control task. Thus, we employ Eq. (3) in this work.

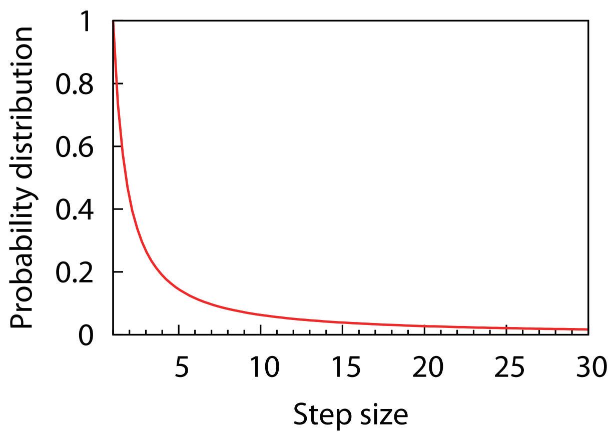


Fig. 1 Lévy probability distribution

3. SIMULATED SWARM ROBOT AND ENVIRONMENT

According to our previous work using the swarm mobile robots [9], the setting of computer simulations was as follows. Differential wheeled robots (Fig. 2) were used in this experiment. The robot's diameter and height are 0.17 [m] and 0.075 [m], respectively. The robot is equipped with four distance sensors located at the front of the body for measuring the distance to other robots and walls, and two sensors located at both ends of the body for detecting targets (Fig. 3). The maximum detection ranges of the former distance sensor and the latter sensor are 0.3 [m] and 0.2 [m], respectively. The robots are assumed to be equipped with wireless devices, which can compose wireless ad hoc networks and communicate with each other via multi-hop path.

The simulated environment is a square arena with walls (Fig. 4). The length of the wall was set to 20 [m]. At the lower left corner, a wireless base station was placed. The communication range of the wireless device was set to 20 [m]. The connectivity of the wireless communication network is checked based on geometric model [**?**, 4]. At the beginning of each trial, swarm robots were always placed 1 [m] apart at the same initial position, the lower right corner, next to the base station at random orientations (Fig. 4(e)). The cylindrical objects were placed as targets. The radius of the cylinder is 0.11 [m] and the height is 0.22 [m]. Targets were uniformly or non-uniformly distributed over the arena. The number of targets was set at $T \in \{84, 168, 336\}$.

Open Dynamics Engine (ODE) [13] was employed in order to consider dynamics of robots and the interaction between robots and environment.

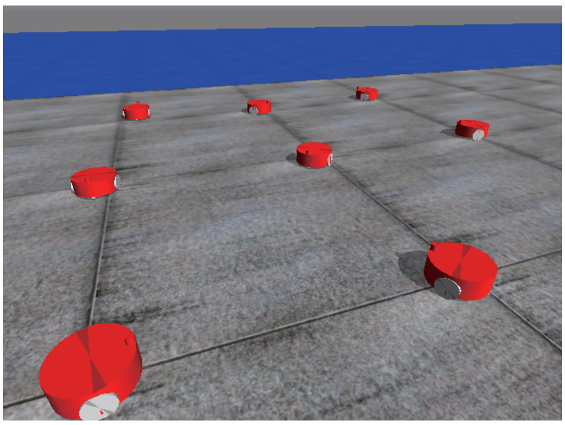


Fig. 2 Differential wheeled robots in an ODE simulation

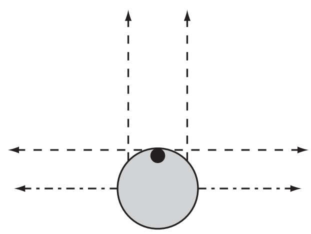


Fig. 3 Ray of the distance sensors (dash line) and the target detection sensors (dot-dash line)

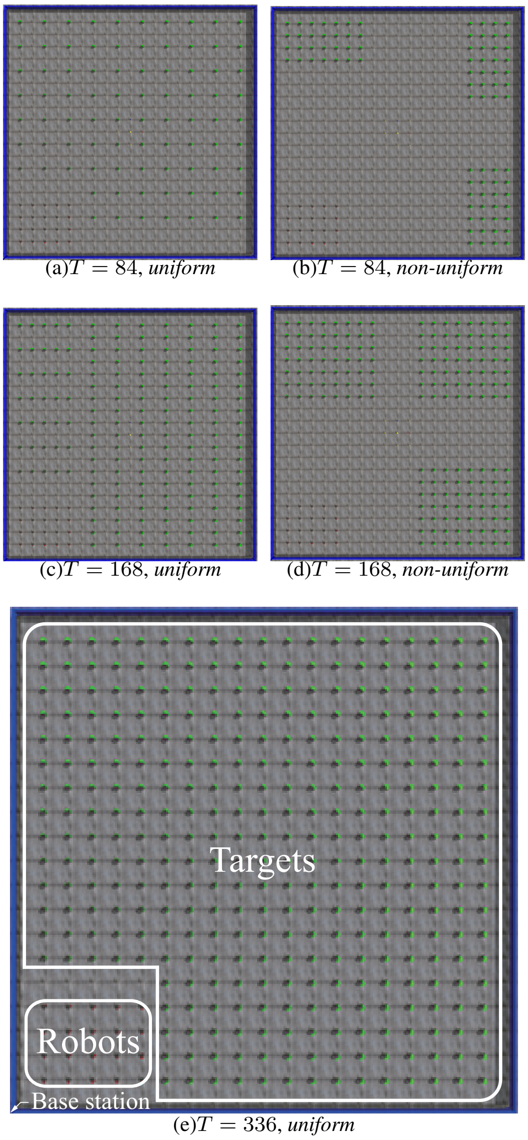


Fig. 4 Set up for computer simulation: distribution of targets

4. CONTROLLER

4.1. Subsumption architecture

Subsumption architecture (SSA) [14] is employed as a format to describe behavior of individuals which compose swarm robotic network according to the setting of our previous work [9]. Fig. 5 shows a layer structure of SSA implemented in this swarm robots. The SSA to achieve the control task in this study is composed of the following three layers: *transmission*, *obstacle avoidance* and *target exploration*. A capital I in a circle in Fig. 5 indicates *inhibition* by which a lower layer is inhibited when an upper layer is activated. Each layer is composed of some modules connected to each other.

Behavior of each layer can be explained as the following; In the target exploration layer, the *explore* module sends messages to one of the following three modules: *forward*, *turn right* and *turn left*, where *forward* means

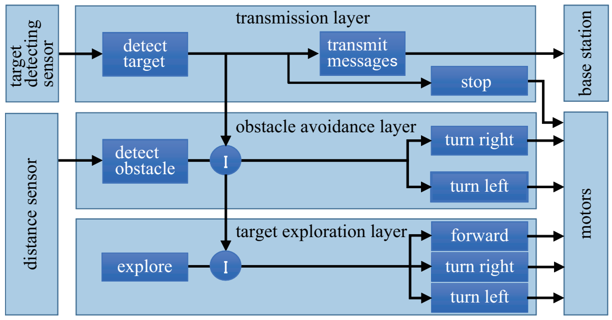


Fig. 5 Layer structure of SSA

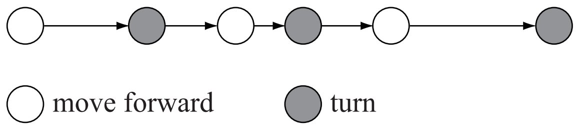


Fig. 6 Transition between move phase and rotate phase in navigation

moving forward and *turn right* (*left*) rotating clockwise (counter clockwise) at the position. In the obstacle avoidance layer, the *detect obstacle* module sends messages to either *turn right* or *turn left* according to the sensory inputs from distance sensors described in Sect. 3, in order to avoid the obstacles which the robot faces. In the transmission layer, the *detect target* module sends messages to the *transmit messages* module and the *stop* module when the sensory inputs from the sensors for detecting targets are beyond a threshold. The *transmit messages* module transmits messages to the base station via intermediate relay robots. The *stop* module sends messages to its own motors to stop them.

4.2. Implementation of Lévy flight in the SSA

Lévy Flight (Sect. 2) is implemented in the target exploration layer (Fig. 5). The details are described in the following subsections.

For the differential wheeled robots assumed to be used in this study, it is difficult to simultaneously move forward with a regular step size and rotate in the predetermined direction. Therefore, the whole steps are divided into the rotation phase and the move-forward phase (Fig. 6), between which the transition occurs at 100%. In the rotation phase, a robot determines the direction of rotation and selects an angle of rotation randomly from $\{45, 90, 135\}$ degree. Then, a robot rotates until reaches the desired angle (the *turn right* or *turn left* module in Fig. 5). In the move-forward phase, a robot moves forward driving two wheels (corresponding to the *forward* module in Fig. 5). A step size in the move-forward phase is determined according to a Lévy probability distribution described in Sect. 2. In our previous experiment using the swarm mobile robots [9], the execution time of one step size in the move-forward phase is set at 6 sec based on the results in the preliminary experiment. This corresponds to setting the minimum movement in the move-forward phase for a constant angular velocity of the wheel. Practically, the execution time of one step size (minimum movement time) must be determined suitable for the area of the environment. In this work, we define w_0 as the minimum movement time and investigate the effect of it on the performance of Lévy flight. Therefore, the execution time in the move-forward phase is w_0 multiplied by a random value w according to a Lévy probability distribution(Eq. (3)). Precisely, the minimum movement can be calculated as $w_0 w$ multiplied by both the radius of the wheel and the angular velocity.

5. EXPERIMENT FOR CONSTANT MINIMUM MOVEMENT TIME

5.1. Setting of computer simulations

A series of computer simulations have been conducted varying the number of robots $N \in \{5, 10, 15, 20\}$ and the minimum movement time $w_0 \in \{1, 5, 10, \cdots, 30\}$ [sec/step] described in Sect. 4. One trial ends when $360,000$ steps (3600 sec) are performed. This experiment investigated the performance of Lévy flight formulating target detection rate as $T(t)/T$, where $T(t)$ is the number of targets detected by swarm robots at t time step. We conducted 50 independent runs varying initial orientations. All results were averaged over 50 runs.

5.2. Experimental results

Figs. 7 to 9 show the average detection rate at each time step for w_0 and T with $N = 5, 15, 20$. The final detection rate converged to 100 % for all the w_0 except for $N = 5$. No significant differences in the final detection rate were observed for w_0 with $N = 15, 20$. The detection rate in the search process (we call this a search speed in the reminder of this paper) for $w_0 = 5$ was the largest among all the w_0. The speed was smallest when $w_0 = 1$ or 30. It becomes smaller with the increase of w_0 over the range $10 \leq w_0 \leq 30$. Thus, the optimal value is identified, which results in the fastest speed over the range of w_0. Increasing w_0 had the same effect for the target distribution and N.

Fig. 10 shows the average detection rate at each time step for N and T with $w_0 = 5$, which was the optimal value in this experiment. The final detection rate converged to 100 % for all the T except for $N = 5$. The speed increased with the increase of T for each N. The speed for *uniform* were larger than those for *non-uniform*. This result would be valid because targets are relatively widely distributed for larger T with *uniform* due to no overlap between targets in this simulation. This results in early detection of targets; more targets are distributed near the initial positions of the swarm robots. The speed increased with the increase of N for each T.

6. EXPERIMENT FOR AUTOMATIC UPDATE OF MINIMUM MOVEMENT TIME

In the previous section, we found that the target search speed has the optimal value for w_0. Probably, the optimal value depends on the area of environment. The optimal value for w_0 would be determined based on the intuition and experience of the designer or tuned by hand of the designer in SR until the desired performance is obtained. From the viewpoint of automatic design methods, automatic parameter setting would be possible as an alternative method. In this section, I propose an automatic update method of w_0 in the search process based on the frequency of target detection. Additional computer simulations were conducted in order to evaluate the performance of the proposed update method.

6.1. Update rule of w_0

w_0 for each robot is updated in the following way:

$$w_0 \leftarrow \begin{cases} w_0 - \Delta w_0, & \text{if } s = 1 \text{ and } w_0 > w_{0\min} \\ w_0 + \Delta w_0, & \text{if } s = 0 \text{ and } w_0 < w_{0\max} \\ w_0, & \text{otherwise,} \end{cases} \quad (4)$$

where $w_{0\min}$, $w_{0\max}$ and s are the lower, upper value of w_0 and the flag to detect a new target, respectively. Δw_0 was set at 1. According to the results obtained in the previous section, $w_{0\min}$ and $w_{0\max}$ were set at 1 and 30, respectively. At the beginning of each trial, w_0 for each robot is initialized as $w_{0\min}$. s is defined as follows;

$$s = \begin{cases} 1, & \text{if a target detected and } \Delta t > 5 \\ 0, & \text{if } \Delta t > 10 \\ -1, & \text{otherwise,} \end{cases}$$

where Δt [sec] is the time passed since when the robot detected the previous target or when Δt is reset. Δt is reset at 0 when w_0 is updated according to Eq. (4).

6.2. Experimental results

The setting of computer simulations were the same as those of the previous section, except for updating w_0. Figs. 11 to 13 show the average detection rate at each time step for the constant and updating w_0 and T with $N = 5, 15, 20$. The results with the constant $w_0 \in \{1, 5, 10, 30\}$ are those in the previous section. The final detection rate converged to 100 % for the updating w_0 except for $N = 5$. The speed for the updating w_0 was between those of $w_o = 5$ and $w_0 = 30$. They outperformed the worst results for the constant w_o although they did not outperform the best results for the constant w_o at any time step.

7. CONCLUSIONS

This paper investigated the performance of Lévy flight in targets detection problem varying the minimum movement time of Lévy flight and proposed the update method of it through a series of computer simulations. The results suggest that the search efficiency of Lévy flight has an optimal value for minimum movement time and the performance of the update method fell between those of the best and worst parameter setting for minimum movement time.

We could improve the update method of minimum movement time of Lévy flight with regard to setting initial values, e.g., setting not constant values but random values. Future work will investigate the performance of the propose method in a dynamic environment.

REFERENCES

[1] M. Brambilla, E. Ferrante, M. Birattari, M. Dorigo, “Swarm Robotics: A Review from the Swarm Engineering Perspective,” *Swarm Intelligence*, Vol.7, No.1, pp.1-41, 2013.

[2] E. Şahin, “Swarm Robotics: From Sources of Inspiration to Domains of Application,” Lecture Notes in Computer Science, Vol.3342, pp.10-20, 2005.

[3] A. Ghosha, S. Das, “Coverage and connectivity issues in wireless sensor networks: A survey,” *Pervasive and Mobile Computing*, Vol.4, No.3, pp.303-334, 2008.

[4] Y. Katada, “Connectivity of Swarm Robot Networks for Communication Range and the Number of Robots Based on Percolation Theory”, *Proceedings of the 2014 IEEE/SICE International Symposium on System Integration*, pp. 93–98, 2014.

[5] Y. Katada, K. Kogo, “Development of the Shortest Path Display System Using Swarm LED Indicators Based on Signal Strength of Wireless Communication”, Proceedings of the 2017 IEEE/SICE International Symposium on System Integration, 2017.

[6] G. Viswanathan, V. Afanasyev, S. Buldyrev, E. Murphy, P. Prince, H. Stanley, “Lévy flight search patterns of wandering albatrosses”, *Nature*, Vol.381, pp.413–415, 1996.

[7] N. Humphries, H. Weimerskirch, N. Queiroz, E. Southall, D. Sims, “Foraging success of biological Lévy flights recorded in situ”, *Proceedings of the National Academy of Sciences of the United States of America*, Vol.109, No.19, pp.7169–7174, 2012.

[8] P. Lévy, *Theorie de l’Addition des Veriables Aleatoires*, Gauthier-Villars, 1937.

[9] Y. Katada, A. Nishiguchi, K. Moriwaki, R. Watakabe, “Swarm robotic network using Lévy flight in target detection problem”, *Artificial Life and Robotics*, Vol.21, No.3, pp.295–301, 2016.

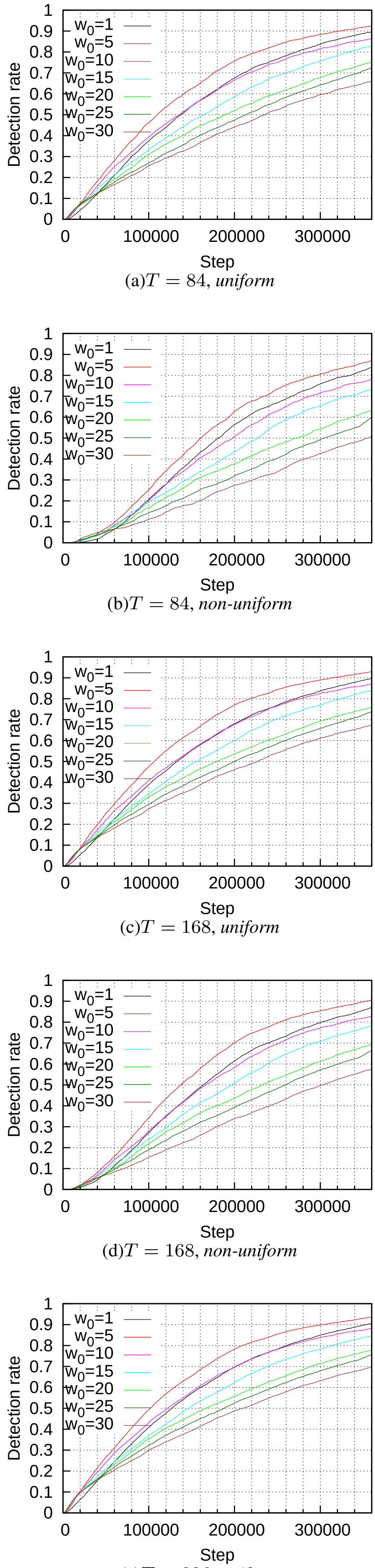
[10] Y. Katada, “Swarm Robotic Network Using Lv́y Flight for Exploration –Computer Simulation for Sweeping”, *Transactions of the Society of Instrument and Control Engineers*, Vol.54, No.1, pp.22–30, 2018 (Japanese).

[11] C-Y. Lee, X. Yao, “Evolutionary Programming Using Mutations Based on the Lévy Probability Distribution”, *IEEE Transactions on Evolutionary Computation*, Vol. 8, pp. 1–13, 2004.

[12] H. Koyama, A. Namatame, “Comparison of efficiency of Random walk based search and Levy flight search”, *Information Processing Society of Japan*, Technical Reports (20), pp. 19–24, 2008 (in Japanese).

[13] Open Dynamics Engine (ODE). http://ode.org/.

[14] R. Brooks, “A Robust Layered Control System for a Mobile Robot”, *IEEE Journal of Robotics and Automation*, Vol.2, No.1, pp.14–23, 1986.



(a)$T = 84$, *uniform*

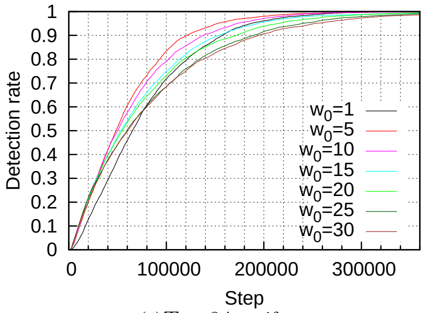
(b)$T = 84$, *non-uniform*

(c)$T = 168$, *uniform*

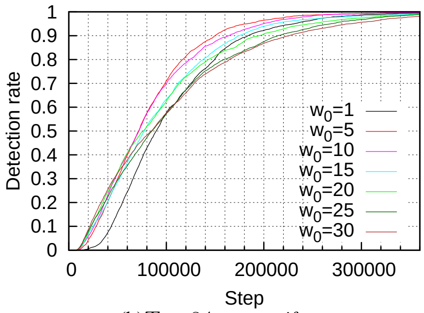
(d)$T = 168$, *non-uniform*

(e)$T = 336$, *uniform*

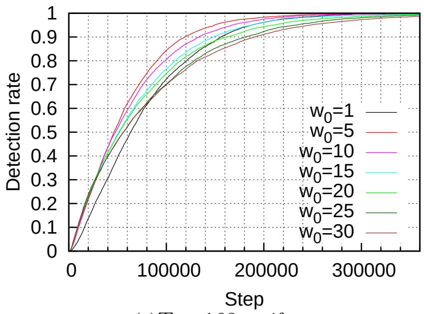
Fig. 7 Average detection rate for each time step with $N = 5$



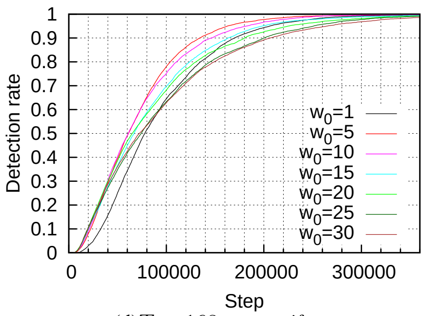
(a)$T = 84$, *uniform*



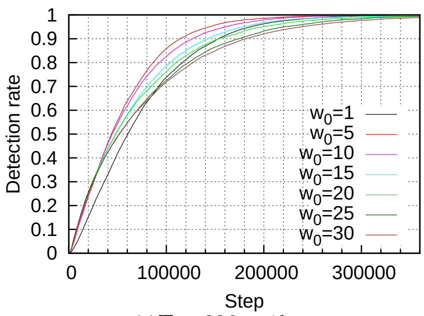
(b)$T = 84$, *non-uniform*



(c)$T = 168$, *uniform*

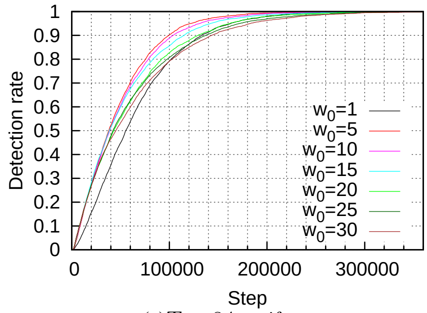


(d)$T = 168$, *non-uniform*

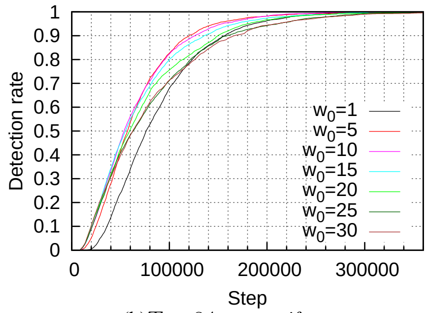


(e)$T = 336$, *uniform*

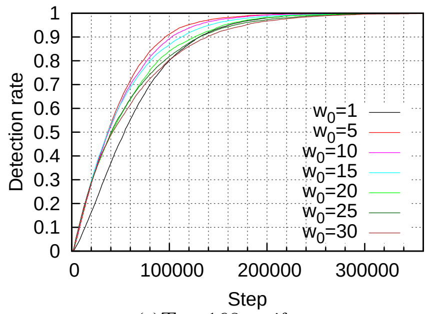
Fig. 8 Average detection rate for each time step with $N = 15$



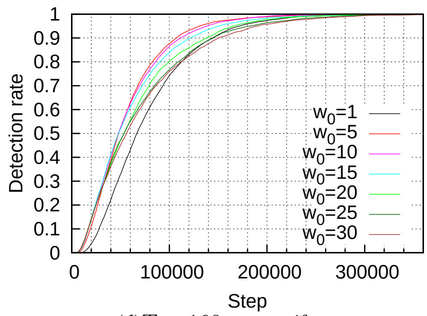
(a)$T = 84$, *uniform*



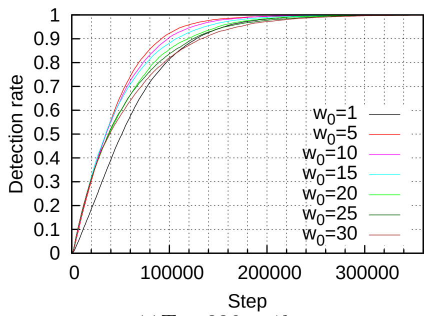
(b)$T = 84$, *non-uniform*



(c)$T = 168$, *uniform*

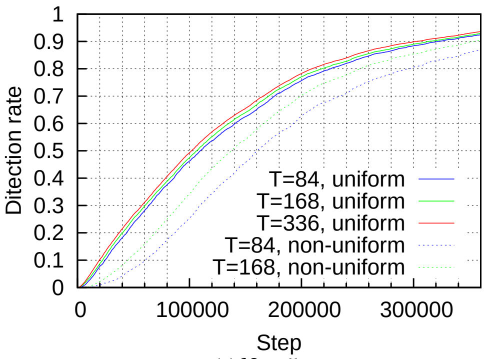


(d)$T = 168$, *non-uniform*

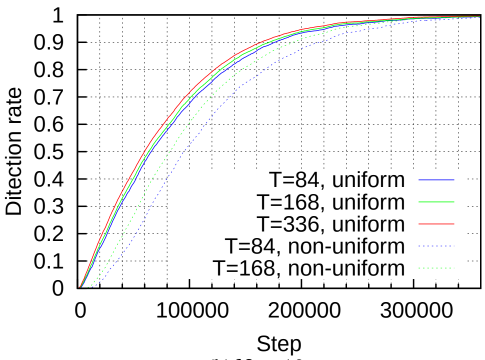


(e)$T = 336$, *uniform*

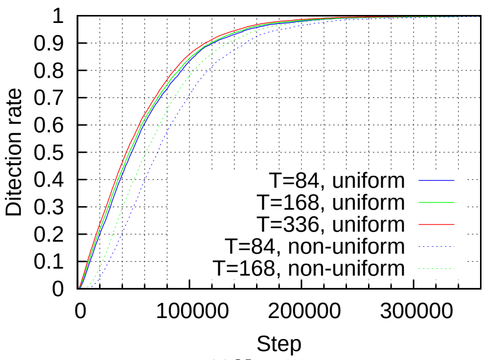
Fig. 9 Average detection rate for each time step with $N = 20$



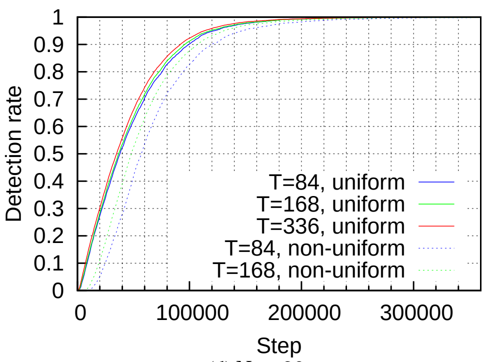
(a)$N = 5$



(b)$N = 10$

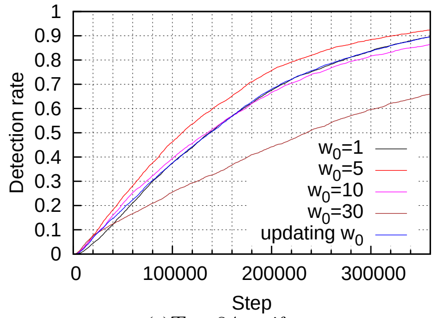


(c)$N = 15$

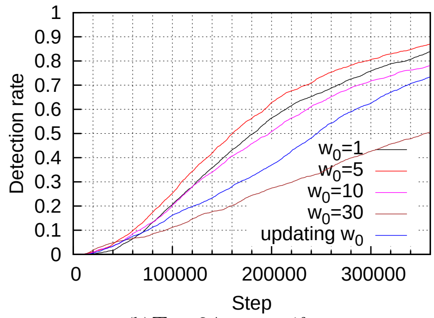


(d)$N = 20$

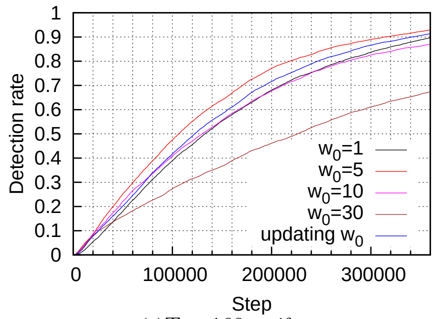
Fig. 10 Average detection rate for each time step with $W_0 = 5$



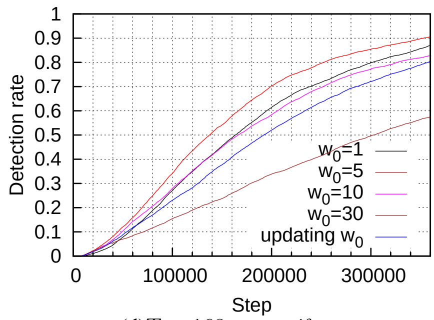
(a)$T = 84$, *uniform*



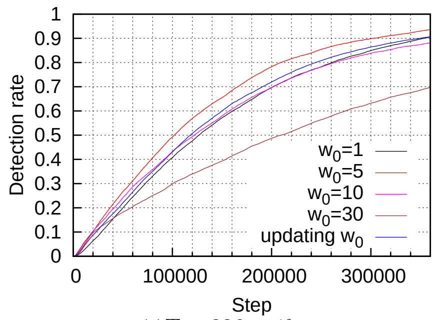
(b)$T = 84$, *non-uniform*



(c)$T = 168$, *uniform*

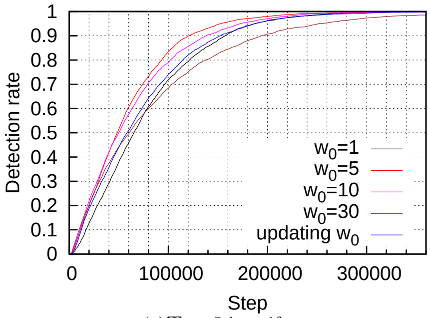


(d)$T = 168$, *non-uniform*

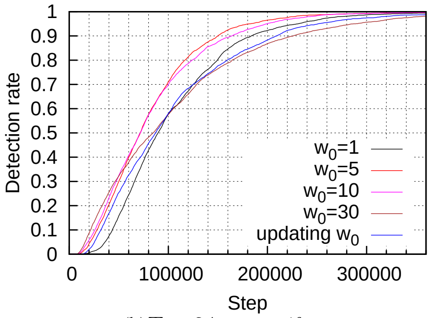


(e)$T = 336$, *uniform*

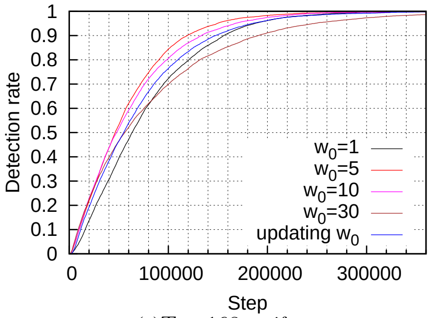
Fig. 11 Average detection rate for constant and updating w_0 with $N = 5$



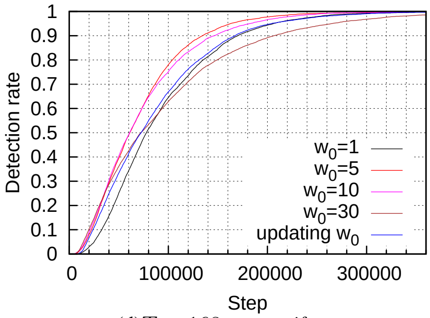
(a)$T = 84$, *uniform*



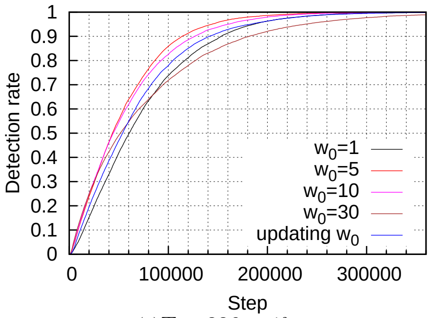
(b)$T = 84$, *non-uniform*



(c)$T = 168$, *uniform*

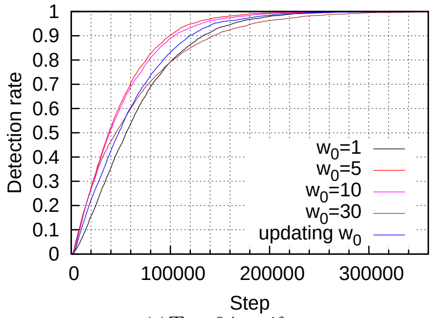


(d)$T = 168$, *non-uniform*

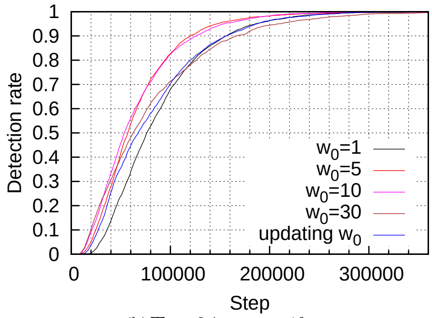


(e)$T = 336$, *uniform*

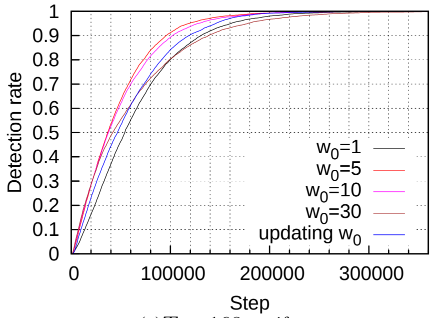
Fig. 12 Average detection rate for constant and updating w_0 with $N = 15$



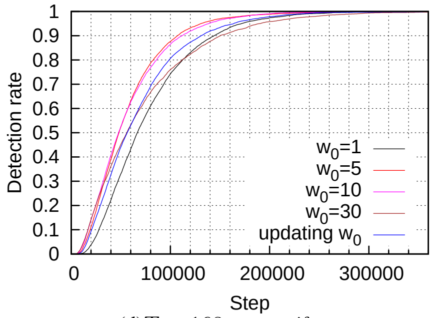
(a)$T = 84$, *uniform*



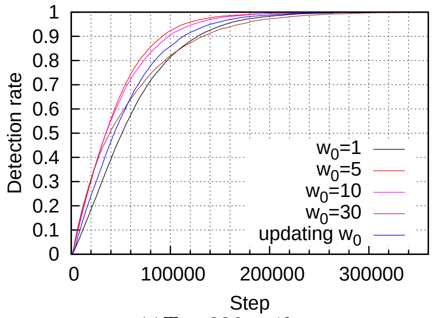
(b)$T = 84$, *non-uniform*



(c)$T = 168$, *uniform*



(d)$T = 168$, *non-uniform*



(e)$T = 336$, *uniform*

Fig. 13 Average detection rate for constant and updating w_0 with $N = 20$